TOWARDS PREDICTIVE MODELLING AND OPTIMIZATION OF MACHINING PERFORMANCE OF ALUMINIUM COMPOSITE

A SYNOPSIS

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1. INTRODUCTION

Materials had been a requirement for the man-kind from the earlier stages of the development. Presently, anything seen around can be linked to a specific application of material or alloy. Materials and alloys possess inherent properties that can be used for a wide range of applications. The scarcity of the fossil fuels had led to a newer area of development which is material with better strength to weight ratio, in automobiles. The space applications also require to reduce the weight thereby improving the payload capacity of the launch vehicles.

The composite materials have entered the arena of material science due to its inherent capabilities and characteristics as well as its flexibility to be adapted to a specific situation. Composite materials are the materials containing more than one constituent, but unlike alloys, the constituents exist in their basic form in the final composite material. The major example of composites is the concrete, where the steel rods and cement are mixed. The inherent properties of both (Steel rods capable of handling tensile load and cement capable of handling compressive load) is used for the creation of this composite providing both tensile and compressive strength for the final product. Composite materials retain the properties of the individual constituents, unlike in the case of alloys, where the mixing creates a material with a different material property as witnessed by Iron- Carbon report. The advantages that can be observed in the composite materials are

- Improved strength to weight ratio
- Same matrix and reinforcements can create different composites with different material properties.
- The composite is heterogeneous which means that the composites can be manufactured according to the loads acting on the component.
- The manufacturing cost of a composite component is lower when compared to an advanced material.

These advantages have ignited an interest for the present industries to switch over to composites for development of their products. The intrusion of composites can be seen in all the present-day industries, which mainly focusses on weight reduction, improved strength and life, improved performance in adverse conditions. These materials have

squeezed their way into automobile, space and nuclear industries due to their inherent capabilities and advantages. Composite materials can be considered as the material for the present requirements in the different industries. A properly designed and developed composite material can satisfy all the conditions laid down by the designer.

The Metal Matrix Composites (MMC) have been identified to be one of the major composites in the last decade due to its capability to handle different requirements of a designer with minor modification in the material properties. The MMCs have been employed in the present-day industries due to this capability.

The major challenge faced by the MMCs is the machining of the composites to the required dimensions, tolerances and fits. The conventional machining techniques were identified to be expensive for the machining of these composites due to the premature tool wear, lower productivity due to slow operations etc. The non-conventional machining techniques, especially the Electric Discharge Machining has been identified as the option which can provide the required dimensional stability and reproductivity. The surface finish can also be enhanced without secondary machining requirements like grinding, if the input parameters are optimised for the required output. Most of the works identified the major contributing input parameters as current (A), pulse-on-time (t_{on}), pulse-off-time (t_{off}) (for Electric Discharge Machining (EDM)) and wire feed rate (for wire EDM).

The Mathematical modelling technique provide a quick and reliable prediction for the required output parameters based on the input parameters applied. The major advantages that a mathematical model can provide are

- Identify the most contributing input parameter for a specific output parameter.
- Provide a regression equation which can be applied to predict the value of the output parameter based on the input parameters considered.

2. LITERATURE REVIEW

Literature survey was carried out in order to understand the works carried out in the recent period in the EDM of Aluminium alloy-based metal matrix composite materials. Based on the thorough literature survey, the research gap and objectives were identified.

Suresh et al. [1] adopted grey relational analysis to optimize the parameters such as peak current, pulse-on-time and wire feed rate for the output parameters of kerf width and surface roughness for varying percentage of B_4C in Al6351-SiC composite. The importance of hardness of a material in the EDM machining process was identified by Marafona [2]. Ishfaq et al. [3,4] carried out a comprehensive investigation on the optimization and surface topology of the output parameters in the EDM machining of Al6061 -7.5%SiC composites.

Muniyappan et al. [5,6] carried out an experimental investigation on the Al6061 based composite in wire EDM and analysed the kerf width and the surface roughness based on the input parameters. Murugesan and Balamurugan [7] developed an experimental analysis using grey relation method for Al6061 reinforced with 15% SiC. The experiment was also conducted using change of polarity of the workpiece. It was identified that the current was the significant contributor in the output parameters of MRR and surface roughness. It was also identified that the negative polarity for the workpiece provided better results. Singh et al. [8] conducted ANOVA based analysis on Al6061 with 10% SiC. The work identified that the increase of current and pulse-on-time increased the parameters considered which were mainly MRR and surface roughness. Prasanth et al. [9] worked on comparing the mechanical properties of Al6061 mixed with SiC and graphite as the reinforcements. It was observed in the work that the increase addition of 12% SiC as the reinforcement increased hardness by 50% and tensile strength by 60% whereas addition of same percentage of graphite reduced the hardness by 25% but increased the tensile strength by 60%. Nagendra Maurya et al. [10] studied the mechanical property of the Al6061 composite with different percentages of SiC. The work identified that the hardness as well as tensile strength of the composite improved by 12.5% with more 5% inception of SiC into the composite.

Uthayakumar et al. [11] worked on functionally graded aluminium matrix composites for machining parameters of surface roughness, electrode wear rate, overcut

and power consumption in EDM. The work aimed for the application of the material in disc brake rotor. The work identified that the current plays a major role in the output parameters. Raza et al. [12] conducted study on Al6061-SiC composite using different electrodes on its performance variation for MRR and surface roughness. It was identified that brass electrode provided a better MRR and surface finish when compared to copper and steel electrodes. Singh et al. [13] worked on the MRR and tool wear rate of Al6061 with copper and brass electrodes. The work identified that tool wear was minimum for copper electrode when compared to brass electrode.

Amruth Babu and Gurupavan [14] worked on the wire EDM machining of Al6061 composite with various percentages of SiC added to it. The work was conducted with the input parameters of current, pulse-on-time, pulse-off-time and wire feed rate. It was identified that the surface roughness reduced with the addition of SiC in the base alloy. The work also identified that the increase in the percentage of SiC reduced the surface roughness. Shyn et al. [15] worked on the optimization of major as well as minor process parameters in obtaining the MRR, EWR and R_a for Al6061- 6% B_4C metal matrix composites (MMC) using Response Surface Methodology. An extensive work was carried out with the input parameters as current, spark on time, spark off time, pulse- on-time, gap voltage, duty factor and flushing pressure.

Sreeraj et al. [16] worked on the wire EDM of Al6351- 10% Rutile composite for machining of micro channels in the electronic circuits. The work aimed at optimisation of the kerf width, kerf depth and the surface roughness using Taguchi method and GRA with PCA technique to develop a hybrid evaluation model for the optimisation of the output parameters. The input parameters considered in the work were current, voltage and wire feed rate. The work identified current as the major contributor for the output parameters. Natraj and Ramesh [17] worked on optimizing the parameters of Al6061 - 5%Al_2O_3- 3%SiC-2% E-glass in EDM. The work identified current and pulse-on-time as the major contributors in surface roughness and MRR.

3. **RESEARCH GAP**

Based on the literature review, the following research gaps were identified:

- The work related to the prediction of output parameters for the multiple composites with same base matrix was scarce.
- The research work with multiple composites were identified to be carrying out the independent analysis for each composite and identifying the optimum input parameters for each of the composites.
- The literatures that dealt with the material properties provide the dependence of the specified material properties on the composites. The variation patterns were not discussed in detail in the works.

4. **OBJECTIVES**

The objectives identified based on the literature review and the research gap are as follows:

- To fabricate the composites based on the literature review.
- To identify the metallurgical and mechanical properties of the composites.
- To carry out the experimentation in EDM and wire EDM machining based on Taguchi method.
- To conduct the mathematical modelling of the experimental results and generate the regression equation.
- Identify the variation of each coefficient in the regression equation based on the hardness and conduct the validation test for the results obtained.

4.1 Proposed Methodology

The research work aims at providing a simple and effective prediction of the output parameters for a specific range of composites with same matrix material. Based on the previous studies, it was identified that a lot of works were carried out for the Aluminium based metal matrix composites with Al6061 as the base matrix for the EDM and Al6351 as the base matrix material for wire EDM. Al6061 based composites were found to be a suitable substitute for pistons and cylinder liners in the automobile applications. Al6351 based composites are being used in nuclear reactors as the control rods. The proposed methodology as a flow chart is depicted in Figure 1.

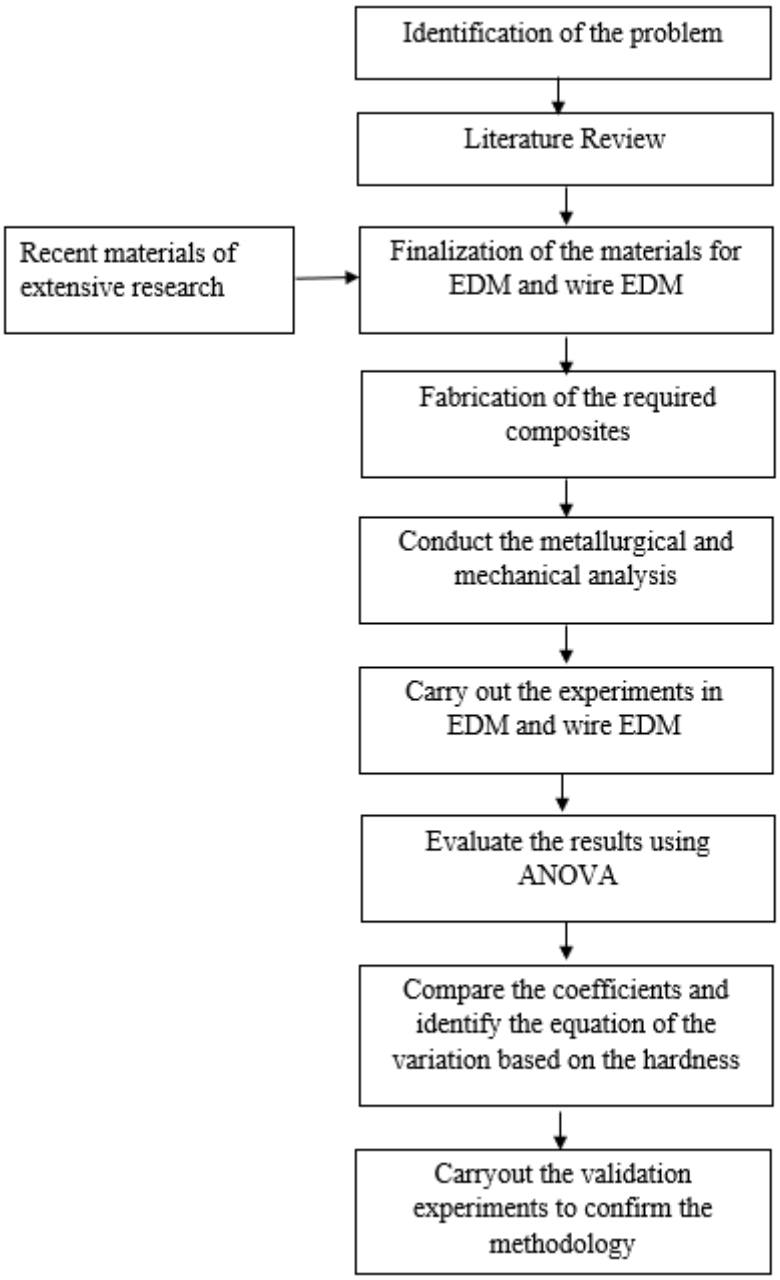
Identification of the problem
Literature Review
Recent materials of extensive research
Finalization of the materials for EDM and wire EDM
Fabrication of the required composites
Conduct the metallurgical and mechanical analysis
Carry out the experiments in EDM and wire EDM
Evaluate the results using ANOVA
Compare the coefficients and identify the equation of the variation based on the hardness
Carryout the validation experiments to confirm the methodology

Figure 1 Methodology for the research work

4.2 Experimental Methodology

4.2.1 Fabrication of composites

The composites for the conducting of experimental investigations were fabricated using stir casting method based on the literature review. The procedure adopted for the development of the sample workpieces are as follows:

Initially the casting die is preheated to 400°C. Al6351/ Al6061 cylindrical rod which is cut to length of 100mm was added into the crucible and kept in the furnace. The base material was heated to the temperature of 850°C for taking it above the liquidous state. The molten metal is stirred using a stirrer at 700rpm and allowed to cool down slowly. The reinforcements were slowly added to the molten metal without stopping the stirring action. The molten mixture is poured into the preheated rectangular die of size 200mmx150mmx30mm to obtain the final composite. The poured composite was allowed to cool down in the die to obtain the final specimen in the solid condition.

The composites specimens developed using the stir casting method were

- Al6061-20%Al_2O_3
- Al6061-1%SiC
- Al6061- 3%SiC
- Al6061- 5% SiC
- Al6061-9%SiC
- Al6061-7.5%SiC
- Al6061-15%SiC
- Al6061-5% Al_2O_3-3% SiC
- Al6351-5%SiC
- Al6351-5% SiC-1% B_4C
- Al6351-5% SiC- 3% B_4C
- Al6351-5% SiC- 5% B_4C
- Al6351- 5% SiC- 6% B_4C
- Al6351- 5% SiC- 8% B_4C
- Al6351-5% SiC- 10% B_4C

4.2.2 Experimental set up

The composites manufactured using stir casting were taken for the evaluation of their mechanical properties. The mechanical properties tested for the fabricated samples were tensile strength and hardness based on the literature [2].

4.2.2.1 Die Sinking EDM

The fabricated workpieces were machined at M/s A1 cosmic tools, Coimbatore. Taguchi method was employed to identify the input parameters for the experimental set up. Three input parameters were considered viz. Current, Pulse-on-time and Pulse-off-time and three levels of each parameter were considered for the experimentation (3^3 matrix). Based on the L9 orthogonal array, the output parameters viz. material removal rate (MRR) and surface roughness (R_a) were measured. The machining was carried out using 25mm diameter copper rod as electrode and for different parameters of current (A), pulse-on-time (T_{on}) and pulse-off-time (T_{off}). After completing the machining process, the specimen was tested for surface roughness in the surface tester, Mitutoyo - surftest SJ

201 manufactured by Mitutoyo, Kanagawa, Japan with the precision level of 0.01μm was employed for the measurement of surface roughness. The MRR was calculated by weighing the specimen prior to and after completing each experimental work and dividing the weight difference with the time consumed for the machining. Altra ZNC7040 model EDM was employed for the machining of the composite. The Voltage was set to a constant value of 210 V and the flushing pressure was kept at 0.5 kg/cm^2. The electrol EDM oil (Viscosity CST at 300 °C is 2.16 cs) was used as dielectric medium for the machining work. The depth of machining was set to 10 mm for all the experiments.

4.2.2.2 Wire EDM Machining

The composite was machined in the wire EDM machine located at M/s A1 cosmic tools ltd, Coimbatore. Nine slots were made on each specimen at different. The tests were conducted for surface roughness (R_a) and kerf width for the three specimens after carrying out the wire EDM machining using a brass wire of 0.25 mm diameter. The deionized water was used as the dielectric. The details of the experimental and measurement set up were as follows:

Machine: Wire EDM (Model:DK7750, M/s Concord United Products Private Limited, Bangalore)

Electrode: Brass wire (0.25 mm diameter)

Dielectric fluid: Deionized water

Flushing flow rate: 9 lit/min

Surface roughness measuring device: Mitutoyo, Model: Surftest SJ-201

Kerf width measuring device: Tool makers' microscope

4.2.3 Mathematical Modelling using ANOVA

The mathematical modelling provides a simple and effective method for the evaluation of the experiments to identify the most contributing parameter. Analysis of Variance (ANOVA) has been a useful tool employed by the researchers for the evaluation of the results obtained in an experiment. Minitab has been a handy statistical software to carry out this analysis of the experiments. It can also provide the equations relating the output and the input parameters considered. Therefore, Minitab software was employed for the construction of ANOVA table for the output parameters and generating an equation to obtain the parameter based on the different values of the input parameters. The coefficients of the input parameters were compared for the different combinations

and plotted for identifying the pattern of variation. The equations for each of the parameters of the ANOVA table were generated based on the hardness of the composite.

5. RESULTS AND DISCUSSION

5.1 Die Sinking EDM

The sample for the machining was evaluated for the microstructural properties and material composition using Scanning Electron Microscope (SEM) and Energy Dispersive X-ray Analysis (EDAX). The sample SEM and EDAX images are provided in Figure 2 and Figure 3

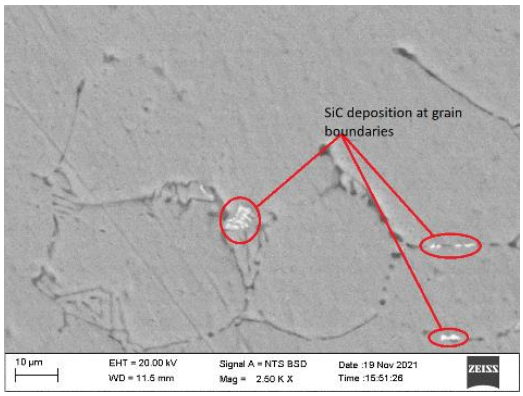

Figure 2 SEM image of the Al6061-3%SiC composite

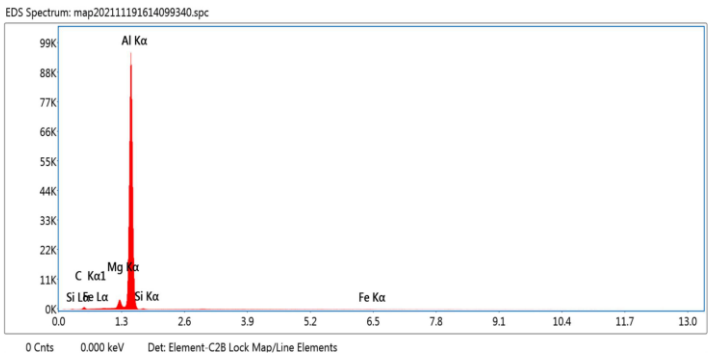

Figure 3 EDAX analysis of the Al6061-3%SiC composite

The SEM and the EDAX images confirmed a proper dispersion of the reinforcements in the composite. In the SEM image the presence of the reinforcements can be clearly observed at the grain boundaries which will be enhancing the mechanical property of the base matrix material. The images provide a confirmation that the experimental values can be used for the further evaluation of the composite.

The regression equations were obtained based on the ANOVA. The hardness of the fabricated samples were evaluated for the developed samples in a hardness tester. The hardness observed for the seven composites are tabulated in Table 1.

Table 1 Hardness of the composites

Sl. No	Composite	Hardness (BHN)
1	Al6061 - 15% SiC	68
2	Al6061 - 20%Al_2O_3	64
3	Al6061 -5%Al_2O_3- 3%SiC	44
4	Al6061 - 7.5% SiC	74
5	Al6061 -3%SiC	65
6	Al6061 - 5% SiC	69
7	Al6061 - 9%SiC	75

Based on the hardness of each of the sample composites, an equation was derived for the coefficients of the considered factors and interactions based on the regression equations. The equations obtained for the coefficients are as follows:

For the Material removal rate (MRR)

$A = -6.34903846\times10^{-05}\times BHN^2+0.00747508\times BHN-0.19561562$--------(1)

$T_{on} = 3.97642998\times10^{-05}\times BHN-0.00090852$----------(2)

$T_{off} = -0.0001084\times BHN+0.0087219$----------(3)

$A^2 = 7.5462\times10^{-06}\times BHN^2-0.0009\times BHN+0.0255$----------(4)

$T_{on}^2 = -1.48915187\times10^{-07}\times BHN+6.05719921\times10^{-06}$----------(5)

$T_{off}^2 = -2.984\times10^{-07}\times BHN^2+3.3609\times10^{-05}\times BHN-0.0009$----------(6)

$A \times T_{on} = -5.8878\times10^{-07}\times BHN^2+7.0927\times10^{-05}\times BHN-0.002$----------(7)

$A \times T_{off} = 2.1696\times10^{-06}\times BHN-0.0002$----------(8)

$Constant = 0.0009\times BHN^2-0.1028\times BHN+2.7796$----------(9)

For Surface roughness (R_a),

$A = 0.0012\times BHN^2-0.148\times BHN+4.6329$----------(10)

$T_{on} = 0.0019\times BHN^2-0.2238\times BHN+6.6334$----------(11)

$T_{off} = -0.1989\times BHN+13.4258$ ----------(12)

$A^2 = 0.0013\times BHN-0.0733$----------(13)

$T_{on}^2 = -2.7272\times 10^{-05}\times BHN^2+0.0032\times BHN-0.0912$----------(14)

$T_{off}^2 = 0.0122\times BHN-0.8286$----------(15)

$A\times T_{on} = 3.914\times 10^{-05}\times BHN^2+0.0042\times BHN-0.1054$ ----------(16)

$A\times T_{off} = 0.0008\times BHN+0.0703$----------(17)

$Constant = 1.0143\times BHN-68.9794$----------(18)

With these equations, the values were tabulated for a trial run in Al6061-1%SiC which was having an BHN value of 61 and compared with the experimental values. The comparison is provided in Table 2.

Table 2 Comparison of the experimental and modelled results

			MRR [g/min]			Surface roughness (R_a) [μm]		
Current (A)	T_{on} (μs)	T_{off} (μs)	Calcula-ted	Experi-mental	% variation	Calcula-ted	Experi-mental	% variation
6	36	7	0.04874	0.0577	15.52	2.5084	3.0380	17.431
6	48	8	0.07596	0.0719	-5.58	5.1701	5.2230	1.012
6	56	9	0.09447	0.0923	-2.35	7.2311	7.4640	3.121
9	36	8	0.07699	0.0924	16.72	4.2179	4.6040	8.386
9	48	9	0.10898	0.1159	6.01	6.9611	6.7750	-2.746
9	56	7	0.12409	0.1091	-13.75	8.8868	8.9170	0.339
12	36	9	0.08115	0.1010	19.65	5.9956	5.6270	-6.551
12	48	7	0.11198	0.1140	1.78	8.4719	9.6090	11.833
12	56	8	0.13652	0.1345	-1.50	11.0784	9.7150	-14.034

5.2 Wire EDM

For the Wire EDM experiment, the composites with base matrix as Al6351 with reinforcements as SiC and boron carbide (B_4C) were considered which were found to have extensive application in the nuclear reactors, especially as control rods. Because of the high precision and surface roughness requirement, the wire EDM machining has been adopted for the machining of the final component. Seven composites were manufactured using the Stir Casting. Six of the composites were used for the generation of the equation and the seventh composite was used for the validation. During the machining process, the condition of the electrolyte was monitored by employing Internet of Things Technique. The SEM and EDAX of the samples were conducted which is shown in Figure 4 and Figure 5.

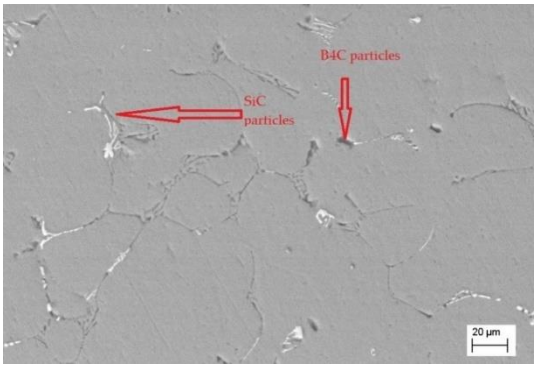

Figure 4 SEM image of the sample

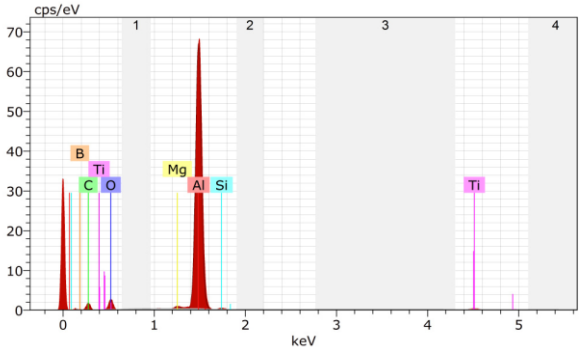

Figure 5 EDAX analysis graph

The mechanical properties of the composites are provided in Table 3

Table 3 Mechanical properties of the Al6351 composites

Composite	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Density (kg/m^3)	Hardness (BHN)
Al–5 wt.% SiC	81.37	105.62	2725	66.81
Al–5 wt.% SiC–3 wt.% B_4C	84.54	109.12	2720	69.3
Al–5 wt.% SiC–5 wt.% B_4C	98.75	120.32	2715	71.58
Al–5 wt.% SiC–6 wt.% B_4C	100.27	124.36	2712	73.1
Al–5 wt.% SiC–8 wt.% B_4C	105.41	129.12	2707	75.1
Al–5 wt.% SiC–10 wt.% B_4C	107.43	132.48	2705	76.78

The equations derived for the coefficients were

For Kerf width

Constant = −0.0036 × BHN + 0.3695----------(19)

T_{on} = 4.1197 × 10^{-5} × BHN − 0.0017----------(20)

WFR = 0.0011 × BHN − 0.083----------(21)

A =−0.0006 × BHN + 0.0254----------(22)

A^2 = 5.1845 × 10^{-5} × BHN − 0.0029----------(23)

A × T_{on} = −1.8732 × 10^{-6} × BHN + 0.0002----------(24)

Current × WFR =−3.329 × 10^{-5} × BHN + 0.0027----------(25)

For Surface roughness

Constant = 2.2023 × BHN − 184.6096----------(26)

T_{on} =−0.0332 × BHN + 2.6548----------(27)

WFR = 0.019 × BHN^2 − 2.7303 × BHN + 97.6943----------(28)

A =−0.1794 × BHN + 15.527----------(29)

A^2 = 0.0047 × BHN − 0.3927----------(30)

A × T_{on} = 0.0034 × BHN − 0.2682----------(31)

A × WFR = 0.0026 × BHN − 0.1099----------(32)

The validation test was conducted on Al6351-5%SiC-1%B_4C sample. The hardness was identified to be 68.3BHN. The result of the validation experiment is provided in Table 4

Table 4 Result of the Validation Experiment – Wire EDM

A	T_{on}	WFR	Kerf width (mm)			Surface roughness (Ra) (μm)		
			Calculated	Experimental	% Variation	Calculated	Experimental	% Variation
12	100	6	0.43158	0.38	−13.57	12.2021	11.1000	−9.929
12	110	10	0.44035	0.4	−10.09	18.5572	15.3500	−20.894

12	120	8	0.46564	0.46	−1.23	17.1707	16.9500	−1.302
16	100	6	0.48011	0.43	−11.65	8.5390	7.6500	−11.620
16	110	10	0.49858	0.46	−8.39	15.3028	14.0200	−9.150
16	120	8	0.52334	0.5	−4.67	12.3727	10.6800	−15.849
20	100	6	0.54915	0.51	−7.68	4.0806	3.5500	−14.946
20	110	10	0.57732	0.54	−6.91	9.2531	8.9000	−3.967
20	120	8	0.60156	0.55	−9.37	4.7795	4.2000	−13.797

5.3 Grey Relation Analysis and Response Surface Methodology

Since the contributing parameters were showing a variable trend, the experimental results were evaluated by using the Response Surface Methodology for Wire EDM and Grey Relation Analysis for EDM. The sample table of the analysis are provided in Table 5 and Table 6.

Table 5 Result of Response Surface Methodology

Std Order	Run Order	Pt Type	Blocks	Current (A)	Pulse duration (T_{on})	Rate of feed of wire (WFR)	Kerf width (KRW)	Surface roughness (Ra)
9	1	2	1	16	100	6	0.23	5.12
14	2	0	1	16	110	8	0.21	10.68
13	3	0	1	16	110	8	0.21	10.68
10	4	2	1	16	120	6	0.22	6.79
8	5	2	1	20	100	10	0.36	11.98
4	6	2	1	20	120	8	0.38	3.94
11	7	2	1	16	100	10	0.23	5.12
7	8	2	1	12	110	10	0.21	8.63
6	9	2	1	16	110	6	0.22	6.79
2	10	2	1	20	100	8	0.39	5.241
15	11	0	1	16	110	8	0.21	6.79
12	12	2	1	16	120	10	0.23	8.56
1	**13**	**2**	**1**	**12**	**100**	**8**	**0.09**	**7.79**
3	14	2	1	12	120	8	0.1	7.646
5	15	2	1	12	110	6	0.12	5.08

Table 6 Response Table – Grey Relation Analysis

Parameter	Level 1	Level 2	Level 3	Max- Min
Current	0.594	0.583	**0.631**	0.048
Pulse on time	0.523	0.602	**0.683**	0.161
Pulse off time	**0.629**	0.553	0.626	0.075

6. RESEARCH FINDINGS

- The work was successfully able to identify a methodology for the prediction of the major output parameters for the die sinking EDM machining of Al6061 based composites and wire EDM machining of Al6351 based composite.
- The hardness value of the composite was found to be the major mechanical property that influences the machining process of the composite.
- The pulse current (40 to 90% contribution) was identified to be the major contributor for the material removal rate as well as surface roughness in a die Sinking EDM irrespective of the composition followed by the pulse-on-time. All the other factors were identified to have comparatively lower influence on these output parameters.
- The Wire EDM experiments showed a variation in the major contributor for different combinations. Pulse current was identified to be a major contributor in most of the cases. The pulse-on-time had a better contribution in the case of intermediate reinforcement percentages, with wire feed rate having higher contribution to the surface roughness.
- Since wire EDM had provided an inconsistent output, response surface methodology (RSM) was conducted to identify the optimum input values which can provide the most favourable results in kerf width as well as surface roughness. It was identified that the optimum values are obtained at lower range of current (12A) and pulse on time (100µs) and medium level of wire feed rate (8m/min).
- The Grey Relation Analysis conducted for the Die-sinking EDM identified lower current (6A), higher pulse-on-time (56µs) and medium pulse-off-time (8µs) provide an optimized result.

- The present method of predicting the output parameters were able to predict the output parameters based on the hardness of the composite with an average error of 8.17% for kerf width, 11.27% for surface roughness in the wire EDM based experiments.
- The variation observed in the Die sinking EDM experiments was 9.3% for MRR and 7.2% for surface roughness.
- This method is a simple and effective method which can be extended for other composites, especially Aluminium based metal matrix composites.

7. ORGANIZATION OF THESIS

- **Chapter 1: Introduction**: In this chapter, the evolution of the composite materials and its importance in the present industrial scenario is discussed. The manufacturing methods adopted for the development of composites were discussed in this section. An introduction about the evaluation techniques and the design of experiments, grey relation analysis along with the latest techniques like Machine Learning and Artificial Intelligence were also discussed in the introduction chapter.

- **Chapter 2**: **Literature Survey**: This chapter deals about the detailed literature survey on the mechanical properties, its influence as well as EDM machining of different Aluminium metal matrix composites employed by the researchers. The research gap was identified, and the objective and the methodology proposed were also reported.

- **Chapter 3: Experimental Procedure:** In this chapter, the manufacturing as well as the experimental and testing procedure for the developed composites were discussed. The evaluation of the mechanical property of the materials were also discussed in this chapter. The quality of the developed composites was evaluated using microscopic, SEM and EDAX images.

- **Chapter 4: Results &Discussions**:

  4.1. Die Sinking EDM: In this sub section, the test conducted on Al6061 based composites were evaluated using ANOVA and the regression equations were generated. The results were compared with the hardness of the material and equations were generated for the prediction of the output parameters based on the obtained

results. The validation experiment and its evaluation are also discussed in this section.

4.2. Wire EDM: This section deals with the evaluation of the experiments and test conducted on Al6351 based composites machined using wire EDM. The ANOVA as well as grey relation analysis was conducted for the composites to identify the major contributor as well as the optimum values for the better output parameters.

4.3. Grey Relation Analysis (GRA): This subsection deals with the Grey Relation Analysis for the selected composites to identify the optimum input values.

4.4 Response Surface Methodology (RSM): This subsection will be employed for the identification of the optimum input parameters using RSM.

4.5 Machine Learning and Internet of Things: This subsection consist of the machine learning technique used for the prediction of the output parameters based on the history. The application of the Internet of Things (IoT) in the machining process also will be discussed under this subsection.

- **Chapter 5: Conclusions**: Based on the results and discussion, the conclusion of the research work and the scope for the future work is reported in this chapter.

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LIST OF PAPERS UNDER REVIEW

1. **Sreeram Hariharan**, Uthayakumar Marimuthu, Thirumalai Kumaran Sundaresan, Suresh Kumar Shanmugam, Rajesh Kanna Govindhan Radhakrishnan, Darius Mierzwinshi, Janusz Walter, Optimization of AA6351-SiC-B_4C Hybrid Composites in Wire EDM Using Grey Relation Technique, *Mechanics of Advanced Composite Structures*.